



Data Analysis and Processing

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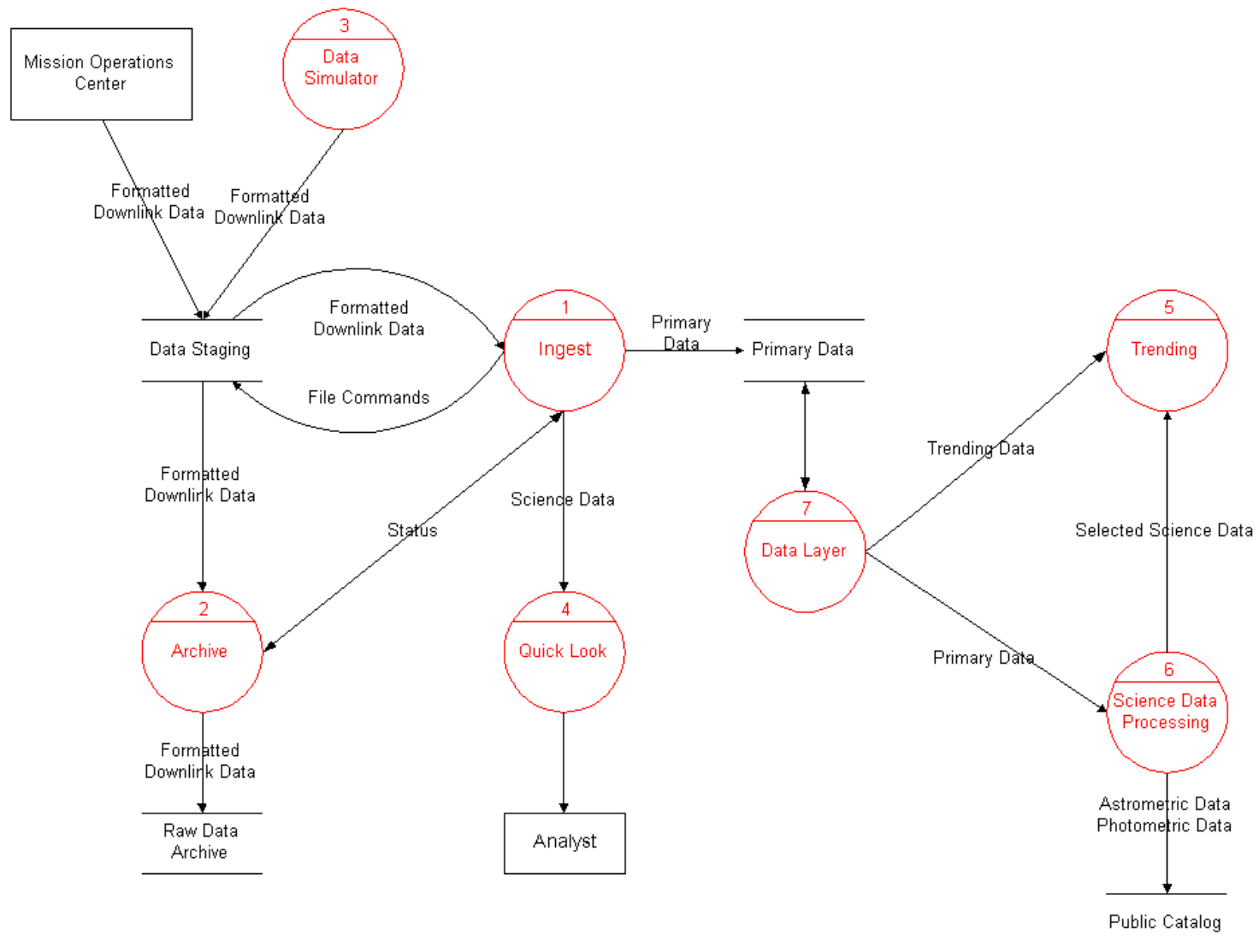
Requirements



- **Accept Data From MOC**
- **Archive Data**
- **Provide Rapid Turnaround Mission Operations Analyses**
- **Assist in MO Anomaly Resolution**
- **Provide Long-Term Instrument Health Analyses**
- **Produce Required Science Data Products**



SOC Design





Design Phase Concepts



- **Pipeline Prototype Effort**
 - **Algorithm Risk Reduction**
 - **Concept Exploration**
 - **Ongoing Process**

- **Iterative Design / Development Effort**
 - **Develop Working Framework**
 - **Modular Development**
 - **Prove Concepts Empirically**
 - **Data Isolation**



SOC Design Next Steps



- **Complete Framework RAD Effort**
 - **Head Start on Development**
 - **Identify Potential Roadblocks**
- **Storage Trade Study**
- **Finalize Interfaces (MOC - SOC; Data Model; HMI)**
- **System Static Modeling**
- **System Dynamic Modeling**
- **Detailed Design**



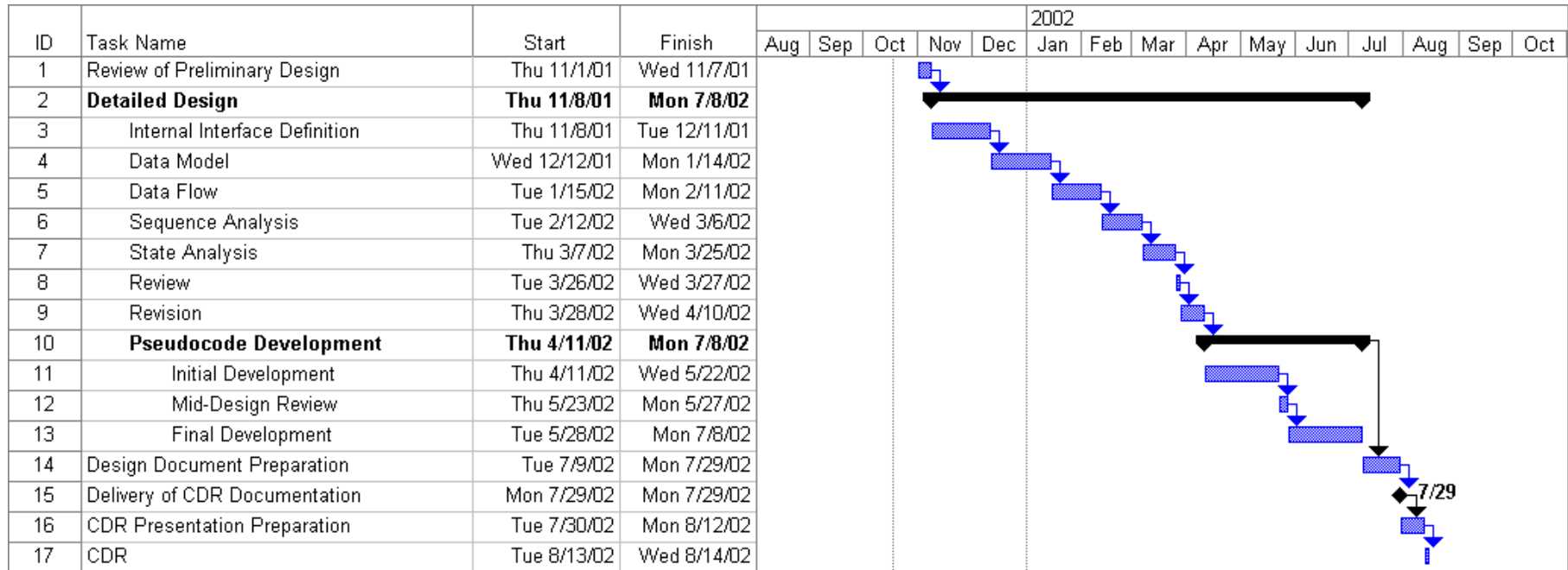
Other Design Phase Tasks



- **Formalize Development Team**
- **Set up Development Environment**
- **Set up CM Environment**
- **Use the Process Prior to CDR**
- **COTS Trades**
- **CASE Trade**
- **Methodology Study**



Detailed Design Schedule



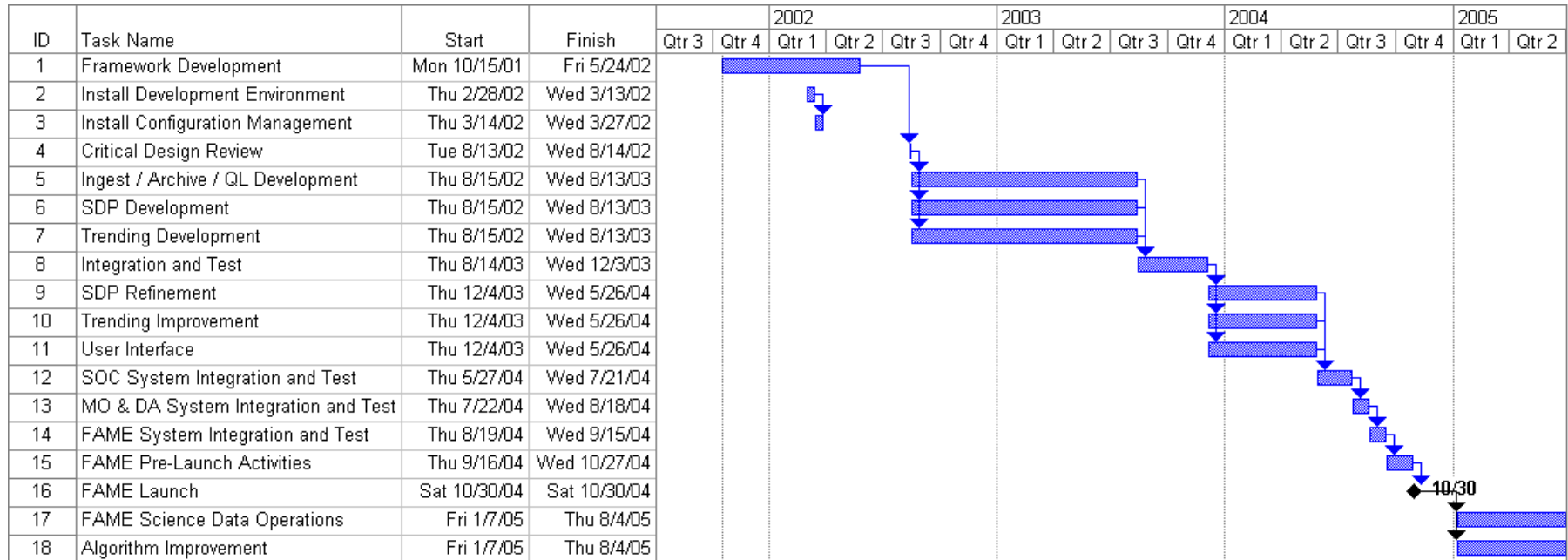


Prototype Schedule

ID	Task Name	Start	Finish
1	Centroiding	Mon 8/20/01	Mon 8/5/02
2	Develop 1-D Observation Centroiding	Mon 8/20/01	Fri 2/22/02
15	Implement 2-D Observation Centroiding	Mon 2/25/02	Mon 6/10/02
25	<i>Identify and Process Pathological Stars</i>	Tue 6/11/02	Mon 8/5/02
30			
31	Global Solution	Mon 8/20/01	Tue 4/9/02
32	Compute O-Cs	Mon 8/20/01	Fri 10/26/01
46	Include Spacecraft Rotation Dynamics	Mon 8/20/01	Fri 3/15/02
64	Implement Global Solution WLS Process	Mon 8/20/01	Fri 12/28/01
82	Develop scheme for Automatic Endpoint Identification	Mon 12/31/01	Fri 3/8/02
86	Test Suite for Global Solution	Wed 2/13/02	Tue 4/9/02
89	<i>Program Star Astrometric Parameter Estimation</i>	<i>Mon 11/5/01</i>	<i>Fri 1/4/02</i>
94	Photometric Reduction	Mon 8/27/01	Tue 4/30/02
95	Update Data Model	Tue 9/4/01	Fri 9/28/01
96	Determine Use of Calibration Data to Address Effects	Mon 10/1/01	Tue 10/30/01
97	Sky/Bias Pipeline	Tue 9/4/01	Mon 12/31/01
101	Photometry Subroutine for Centroiding Module	Tue 9/4/01	Mon 12/31/01
105	Quick and Dirty Photometry	Mon 8/27/01	Tue 9/25/01
109	Identify Primary and Secondary Photometric Stars	Tue 9/4/01	Mon 12/31/01
110	Photometric Calibration Pipeline	Thu 11/1/01	Fri 3/1/02
114	Apply Calibrations Subroutine	Fri 2/1/02	Tue 4/30/02
118			
119	Post-Solution Analysis	Tue 8/6/02	Mon 10/28/02



Production Schedule





Science Data Deliverables



- **Star Input Catalogs (2003)**
- **FAME Catalog A (2008)**
- **Observation Database (2010)**
- **FAME Catalog B (2010)**
- **Technical Reports**



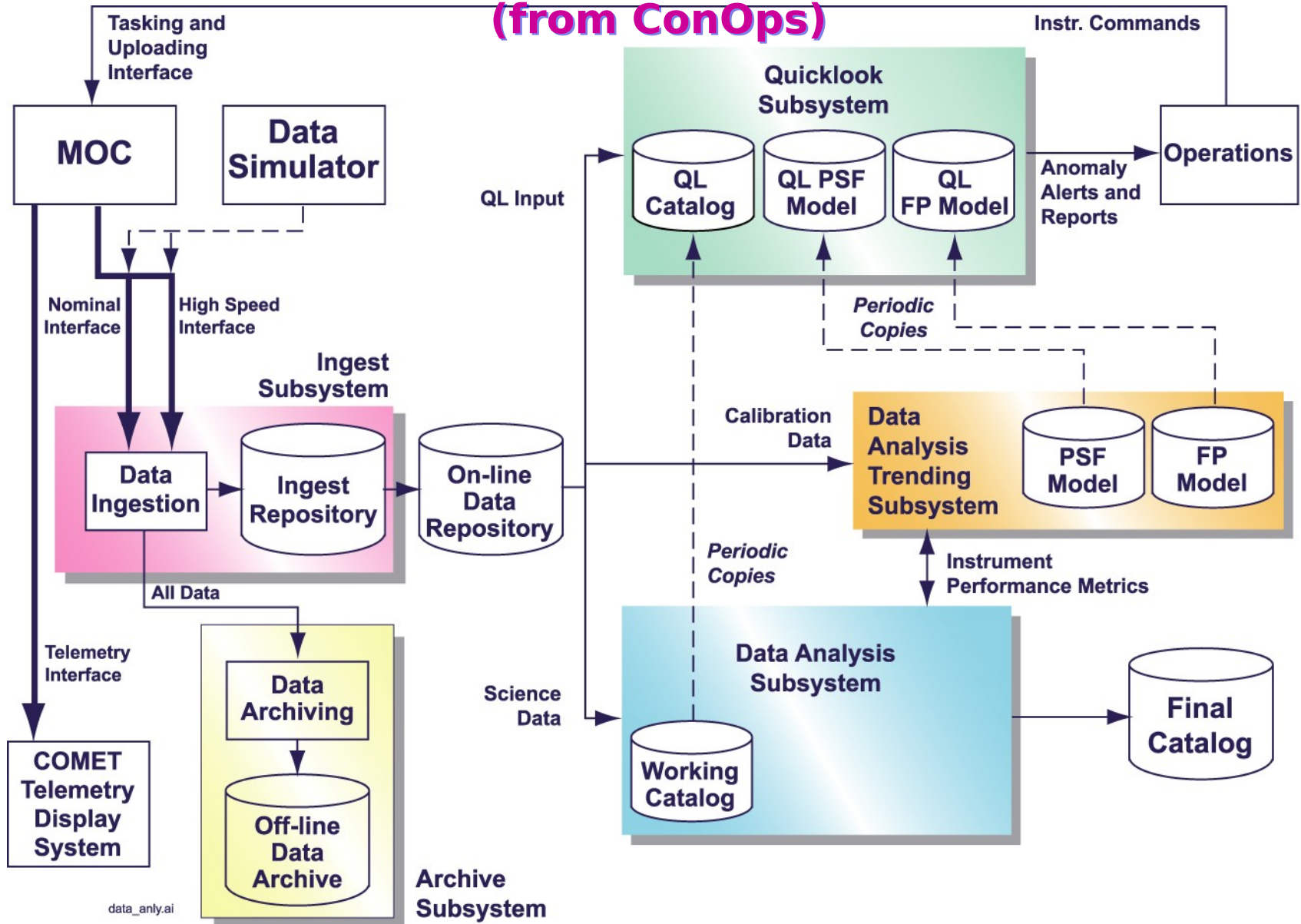
Data Analysis Algorithms

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Data Analysis Pipeline Context

(from ConOps)





Inheritance

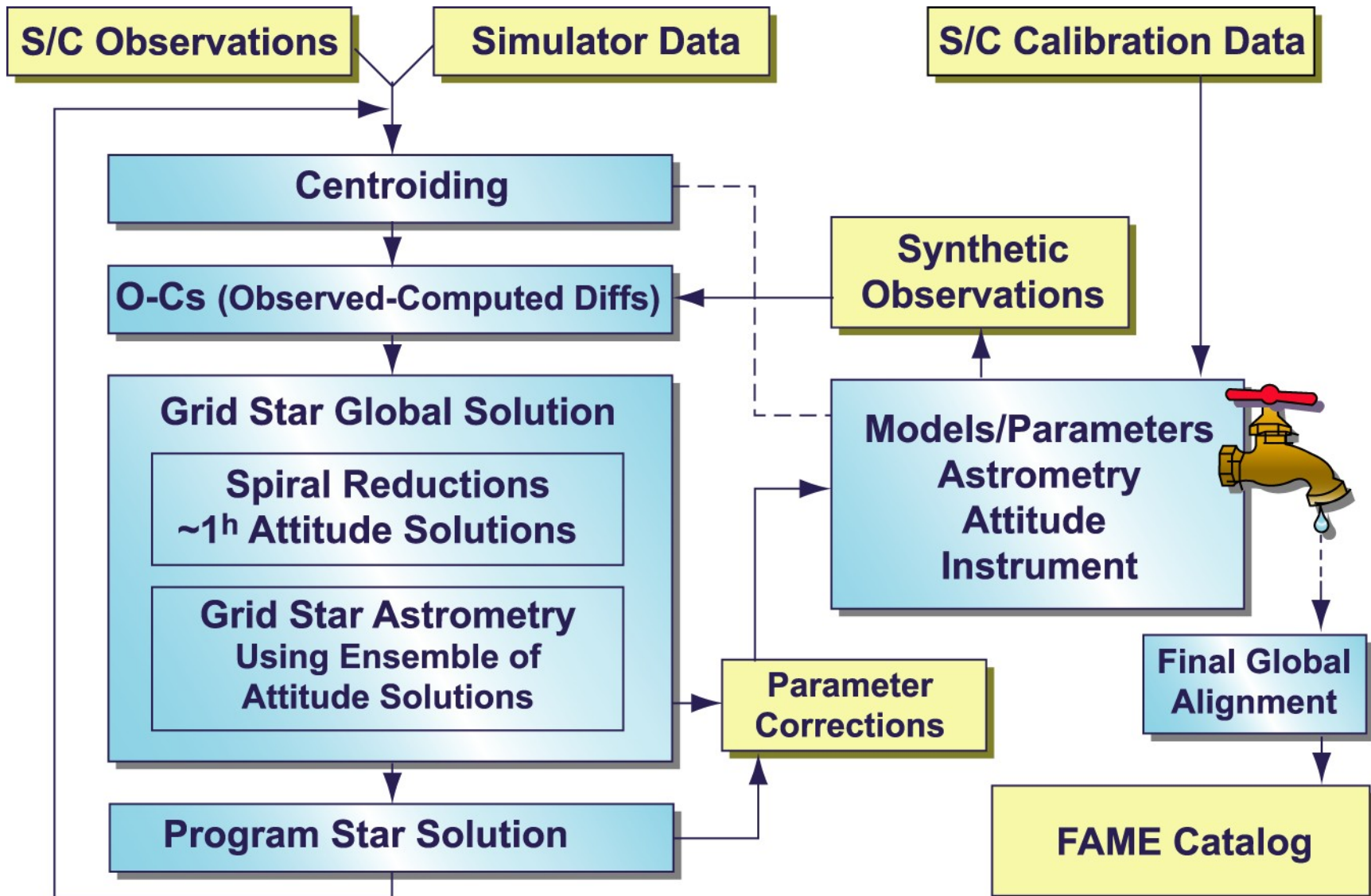


- **Hipparcos (ESA) — Early 1990s**
 - 100,000 Stars in Main Catalog
- **POINTS (SAO) — Studies in Early 1990s**
- **Sloan Digital Sky Survey Astrometric Pipeline — Mid 1990s**
 - 100 Million Objects
- **GAIA Concept and Technology Study Report (ESA) — 2000**
- **Tycho-2 Catalog — 2000**
 - 2.5 Million Stars
- **CCD Astrometry at USNO/Flagstaff — in Progress, Since 1980**
 - USNO - a2.0: 588 Million Stars
- **USNO CCD Astrometric Catalog (UCAC) — in Progress**
 - 60 Million Stars

***Algorithm Details in “Fame Data Analysis Plan”
(Version 2) With References to More Detailed
Developments***



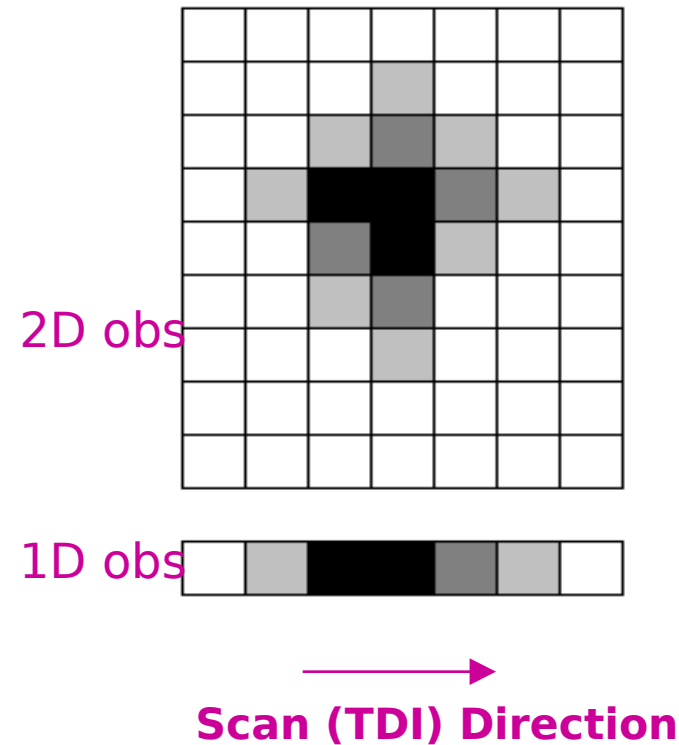
Astrometric Pipeline Overview





Centroiding (1 of 2)

- **Used for Both Astrometric and Photometric Pipeline**
 - **Given: Pixel Intensities Accumulated Over One 2.24-Second Observation; CCD and Star ID, Amplifier Gain, Time Tag, etc.**
 - **Compute for Each Charge Image:**
 - Central Intensity
 - Image Shape Parameters
 - Center Location
 - Sum of All Intensities Within Window
- ⇒ Infer Location of Photon Centroid at Some Well Defined Time, t_i , to 1/350th Pixel for Stars Brighter Than About 12th Magnitude**



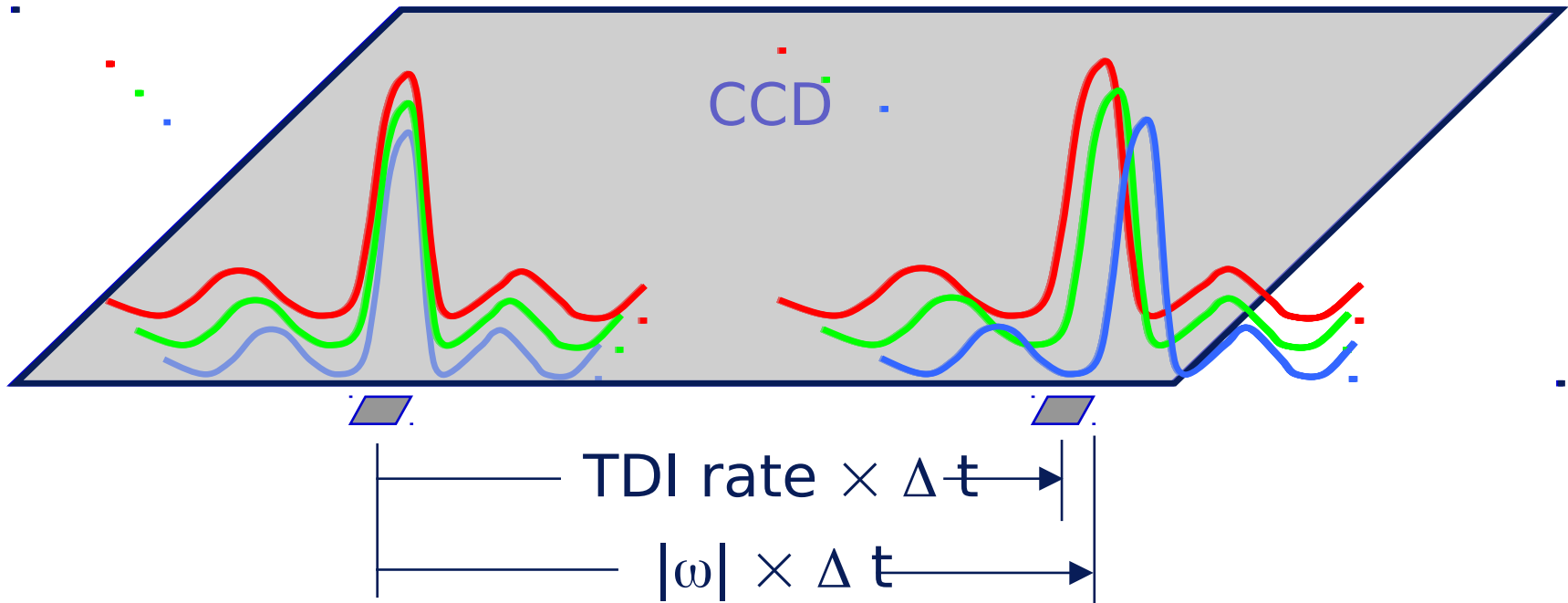


Centroiding (2 of 2)



- **Need to Compute, for Each Observation, a Fitting Function That Duplicates (As Well As Possible) the Parent Function of the Received Pixel-intensity Profile**
 - **Need to Integrate Over Exact Track of Star Image Across CCD**
 - **Need Information on Monochromatic PSFs at Various Locations in the Focal Plane, Lateral Color Shifts, Star Color (From Photometry), Optical Distortion Map, TDI Rate Mismatch, Cross-scan Motion**
- **Tradeoff:**
 - **Accuracy of Fitting Function \Leftrightarrow Size of Systematic Centroiding Errors**
 - **Non-Ideal Fitting Function Propagates Centroiding Biases (As a Function of Pixel Phase) Downstream, Where They Must Be Solved for in the Global Solution**

PSFs to Observation Profiles



- **To Compute Fitting Profile:**

- **PSF As a Function of Color and Position Must Be Integrated Over Star's Spectrum As Received and Over Track of Image Across CCD**
- **In-Scan and Cross-scan "Smearing" Must Be Added in to Account for TDI Rate Mismatch and Precessional Motion, Respectively**



Grid Star Global Solution



- **Given: Initial Model Parameter Values; O-Cs From Modeling and Ancillary Data for Grid Star Observations**
- **Compute: Correction to Model Parameter Values Consistent With Observations**
- **Process Is Linearized Weighted Least Squares (WLS) Estimator:**

$$(O - C)_\alpha = \sum_i \frac{\partial \alpha}{\partial p_i} \Delta p_i + \sum_j \frac{\partial \alpha}{\partial q_j} \Delta q_j + \sum_k \frac{\partial \alpha}{\partial r_k} \Delta r_k$$

Astrometric Parameters **Attitude Parameters** **Instrument Parameters**
 $\sim 6 \times 10^5$ $\sim 3 \times 10^6$ $1-3 \times 10^6 (?)$

- **Complete Simultaneous Solution Not Possible With Current Computers**
 - **⇒ Must Solve for Parameter Subsets in Blocks (Leave Other Parameters Fixed, Tie System Together Through Iteration)**



Solution

CCD Amplifier Gain



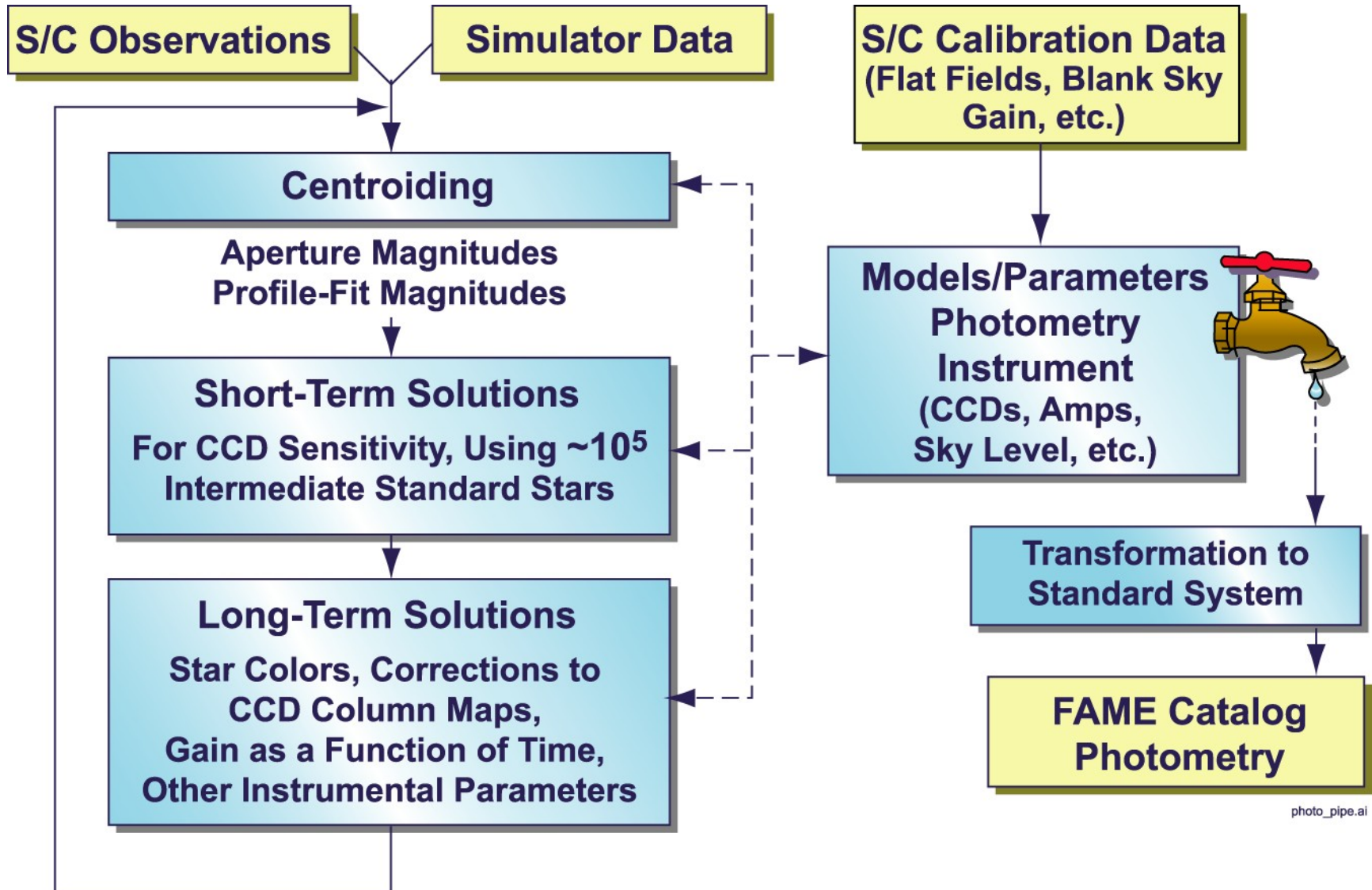
Grid Star Global Solution



- **Two Major Solution Modes:**
 - **“Spiral Reductions”:** One or More Rotations (Observations Over Hours)
 - Grid Star Astrometric Parameters Fixed, Solve for Attitude Parameters and Some Instrument Parameters
 - **“Grid Star Astrometry”:** Many Spirals (Observations Over Months to Years)
 - Attitude Parameters Fixed, Solve for Astrometric Parameters, Spiral Orientations, and Other Instrument Parameters
- **“Fixed” Parameters Are Not Actually Fixed, Just Not Part of the Solution: Can Use Partial Pre-reduction to Obtain Results for Solved-for Parameters Identical to Those That Would Have Been Determined If the Other Parameters Were Part of the Solution – Without the Computational Burden**
- **Experiments Now Underway With Parameterization, Solutions of Different Sizes, Different Combinations of Parameters in Same Solution**



Photometric Pipeline Overview





Pipeline Status



- **Basic Data Simulator Developed and in Use**
- **Prototype Astrometric Pipeline Developed and in Use, Post-Centroiding Through Grid Star Global Solution**
 - **Simulator-Pipeline O-Cs Validated As Effectively Zero for Identical Instrument and Attitude Models and Same Input Catalog**
 - **Expressions for Partial Derivatives for Increasing Number of Parameters Being Developed and Added**
RA, Dec, Coefficients of 3 Time Series for Attitude Euler Angles, Coefficients of Time Series for Basic Angle, CCD Offsets
 - **Various Spiral and Global Solution Tests Completed and in Progress**
 - **Ex: Done: 5.9×10^5 Astrometric Parameters for 1.2×10^5 Stars From 7.2×10^6 obs'ns**
 - **Centroiding Algorithms Developed for Instrument Optics Design Tests; Will Be Integrated Into Main Pipeline Flow**
 - **Realistic S/C Rotation Model (Numerical Integration) Developed and Tested but Not Yet Integrated Into Pipeline – Simple Analytic Models OK for Now**
 - **Many, Many Other Details Still to Be Added – Prototype Pipeline Primarily Intended to Answer Some of the “Big Questions” About Data Analysis Strategy**
- **Prototype Photometric Pipeline Recently Developed and Undergoing Testing**
- **Design for Production Pipeline in Progress**



Algorithm Contributors



Alphabetically, USNO Staff Unless Otherwise Noted:

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Arsen Hajian

Hugh Harris

Greg Hennessy

George Kaplan

Jeongin Lee

Stephen Levine

Valeri Makarov

Dave Monet

Jeff Munn

Marc Murison

Rob Olling

Jim Phillips (SAO)

Jeff Pier

**Bob Reasenberg
(SAO)**

Sean Urban

Norbert Zacharias



Data Analysis Algorithms Background



Astrometric Pipeline Processes (1 of 2)



Data Simulator

S/C Observations + Tracking → MOC → SOC Data Ingest



- **Centroiding**

- Characterizes Intensity and Shape of Each Star Image and Determines Location of Its Center wrt Pixel Coordinates, at Some Well-defined Time t_i

- **A Priori Modeling**

- Using Input Star Catalog, Model of S/C Spin, and Model of Instrument Geometry and Throughput, Predicts Location of Star Images wrt Focal Plane Coordinates at Times t_i ; Computes O-Cs

- **Grid Star Global Solution**

- Using O-Cs, WLS Solution for Adjustments to Spin and Instrument Model Parameters and Grid Star Astrometric Parameters
- $\sim 10^7$ Parameters! Operates in Several Modes, Iteratively:
 - Spiral Reductions: $\sim 1^h$ Attitude Solutions, Astrometric Parameters Fixed
 - Grid Star Astrometry: Attitude Parameters Fixed, Astrometric Solution $>$ Months



Astrometric Pipeline Processes (2 of 2)



- **Program and Science Star Solution**
 - **After Application of Corrections to Spin and Instrument Models, WLS Solution for Adjustments to Program Star Astrometric Parameters Iterations**
- **Iteration**
 - **Iteration of Grid Star Global Solution Blocks; Inclusion of Some Program Stars in Global Solution; Re-centroiding After Photometric Analysis and Maturation of Instrument Model; Final Comprehensive Re-analysis**
- **Post-solution Residual Analysis**
 - **Discovery and Investigation of Trends in Astrometric and Instrumental Parameters**
- **Final Global Alignment**
 - **To ICRS, Using Ground-based Radio Observations of Radio Stars and Some Bright Quasars**



Centroiding Issues (1 of 2)



- **Need Fitting Function to Match Observational Profile (Parent of Received Pixelated Sample) to $<1\%$ to Avoid Centroiding Biases As a Function of Pixel Phase That Are Larger Than the Random Errors**
- **Unlikely to Be the Case Because**
 - Will Only Have Ground-Measured – Not On-Orbit – PSFs
 - Will Only Have Ground-Based – Not On-Orbit – Mapping of Instrument's Optical Distortion and Other Aberrations
 - At Least Initially, the Star's Color Will Not Be Known Sufficiently Well
- **Mismatched Fitting Function \Rightarrow Systematic Centroiding Errors As a Function of Pixel Phase (Also Affects Photometry)**
- **Also Will Have Systematic Errors Due to Incorrect Optical Distortion Mapping**
- **Can the Systematic Errors Be Solved for As Part of the Global Solution? Probably Only If Errors Are Small and Parameter Space Over Which They Are Important Is Very Limited**



Centroiding Issues (2 of 2)



- **Experiments Currently Being Designed Using the Simulator and Prototype Pipeline to Quantify the Problem, Analyze Solution Strategies**
- **Recognition of Close Binary Systems**
- **Effects of Variations in CCD Pixel Sensitivity, Which Are Likely to Be Functions of Time**
 - **Will Have “Flat Fields” From Calibration Observations**
 - **May Be Able to Solve for Sensitivities by Column**
 - **Also a Photometry Issue**



A Priori Modeling (1 of 2)



- **Given: S/C Attitude Data; S/C Tracking Data (Geocentric r, r); and Input Star Catalog**
- **Compute: Position of Star Image on Focal Plane at Given Time t_i for Each Observation *and* Difference Between Image Positions Computed Here and Those Obtained From Centroiding Process; i.e., O-Cs**
- **Requires the Following Transformations:**
 - **Input Star Catalog Astrometric Parameters → Instantaneous Direction of Star As Seen From FAME at t_i , wrt ICRS**
 - Proper Motion, Binary Orbital Motion, Parallax, Aberration, Light-Bending
 - **Direction of Star wrt ICRS → Direction of Star wrt Rotating S/C-Fixed Frame**
 - Euler-Angle Rotations Based on S/C Attitude Determinations
 - **Direction of Star wrt S/C-Fixed Frame → Location of Image Center wrt Specific Pixels on a Specific CCD**
 - Gnomonic Projection, Optical Distortion, CCD Locations and Tilts, etc



A Priori Modeling (2 of 2)



- **Each of These Transformations Has a Set of Model Parameters Associated With It**
 - **Astrometric Parameters (What We Care About)**
 - **Attitude (S/C Rotation) Parameters**
 - **Instrument Parameters**
- **Corrections to Adopted Values of Parameters Are Solved for in the Global Solution; Transformations Performed at This Step Are Good Enough That O-Cs Can Be Expanded As a Linear Combination of Small Corrections to the Parameters**



Grid Star Global Solution Sample Design Matrices

Sample Global Solution Design Matrix



Sorted by Star
(Grid Star
Astrometry)

Star	Obs	Spiral	CCD	Astrometric Parameters (3 per star)															Attitude Parameters (3 per spiral)									Instrumental Parameters					
				A11	A12	A13	A21	A22	A23	A31	A32	A33	A41	A42	A43	A51	A52	A53	R11	R12	R13	R21	R22	R23	R31	R32	R33	H	E	S	I	B	N
1	111	1	4																														
	112	1	2																														
	131	3	3																														
	132	3	4																														
	133	3	3																														
2	221	2	3																														
	222	2	1																														
	223	2	4																														
	231	3	4																														
	232	3	3																														
3	311	1	2																														
	312	1	1																														
	321	2	3																														
4	322	2	4																														
	411	1	2																														
	412	1	3																														
	421	2	1																														
5	422	3	3																														
	521	2	2																														
	522	2	3																														
	523	2	4																														
	524	2	4																														
	525	2	1																														
	531	3	2																														
	532	3	3																														
	533	3	2																														

Sorted by Spiral
(Spiral Reduction)

Star	Obs	Spiral	CCD	Astrometric Parameters (3 per star)															Attitude Parameters (3 per spiral)									Instrumental Parameters					
				A11	A12	A13	A21	A22	A23	A31	A32	A33	A41	A42	A43	A51	A52	A53	R11	R12	R13	R21	R22	R23	R31	R32	R33	H	E	S	I	B	N
1	111	1	4																														
1	112		2																														
3	311		2																														
3	312		1																														
4	411	2	2																														
4	412		3																														
2	221		3																														
2	222		1																														
2	223		4																														
3	321		3																														
3	322		4																														
4	421		1																														
5	521	3	2																														
5	522		3																														
5	523		4																														
5	524		4																														
5	525		1																														
1	131		3																														
1	132		4																														
1	133		3																														
2	231	3	4																														
2	232		3																														
4	422		3																														
5	531		2																														
5	532		3																														
5	533		2																														



Program & Science Star Astrometric Solution



- **Given: Corrected Attitude and Instrument Parameters From Grid Star Global Solution; O-Cs From Modeling and Ancillary Data for Program and Science Star Observations**
- **Compute: Corrections to Astrometric Parameters for Program and Science Stars, Consistent With Observations**
- **Knowing S/C Attitude History and Having a Good Instrument Model, Each 1D Program or Science Star Observation Defines a Line of Position (LOP) on the Celestial Sphere**
- **Straightforward Per-Star Solution for 5 (Sometimes More) Astrometric Parameters From ~1500 Observations**
- **Use Same Partial Derivative Formulas As for Grid Star Global Solution**



Iteration



- **Entire Pipeline Process Is Inherently Iterative:**
 - **Iteration Always Indicated for Linearized WLS Solutions to Ensure χ^2 Minimum**
 - **For the Grid Star Global Solution, Need to Fold Corrections to the Parameters, Determined at Different Steps, Into the Models (Which Affect the O-Cs for All Stars at All Steps)**
 - **Re-Centroiding Will Be Necessary Once Good Photometry Is Obtained for Stars and After Instrument Model Is Mature**
- **Can Eventually Fold Selected Subsets of Program Stars Into the Global Solution When Their Astrometric and Photometric Parameters Become Reasonably Well Known**
 - **Will Provide Higher-Frequency Data for Rotation Model**
- **Various Feedback Loops Will Be Built Into the Pipeline Data Flow, but the Feedback Will Not Be an Automatic Process**



Post-Solution Residual Analysis



- **Effects to Be Looked for**
 - **Multi-Mass Star Systems**
 - **Stellar Variability (From Photometry)**
 - **Trending of Instrumental Parameters With**
 - **Time**
 - **Temperature**
 - **Position on Focal Plane**
 - **Sun or Earth Angle ...Etc.**
 - **Discontinuities and Other Unexpected Results**
- **Some of This Will Require Human Analysis of Plots of Residuals Cut Along Various Dimensions in Parameter Space**
- **“Factor Analysis” Is Also a Potential Tool for Simplifying and Making Sense of the Parameter Covariance Matrix**



Final Global Alignment



- **Final FAME Astrometric Frame Will Be Precise and Internally Consistent, but**
 - Will Have an Arbitrary Alignment to Conventional Reference Systems
 - May Have a Small Net Rotation
- **Goal Is to Tie FAME Frame to ICRF to Within the Errors of the Latter ... and...**
- **ICRF Defined by Positions of Extragalactic Radio Sources ...So...**
- **Need Radio - Optical Intermediaries:**
 - Optically Bright Radio Stars
 - Optically Bright Quasars
- **Scheme Similar to That Used for Aligning Hipparcos Frame**



Photometric Pipeline Processes (1 of 2)



- **Centroiding (*Same As Astrometric Pipeline*)**

- **Basic Calibration**

Calibration Data (Flat Fields, Gain Measurements, DC Level, Etc.) Processed to Provide Effective Gain (Throughput) of Each CCD Column vs Time

- **Instrumental Magnitudes**

Two Types, Determined From (1) Fit of Observation Profile to Template Function, and (2) Sum of All Pixel Values in Observing Window (Aperture Photometry)

- **Short-term Solutions**

Using Set of Intermediate Standard Stars (Analogous to Grid Stars), Develop 1-2 Hour Solutions for Sensitivity of Each CCD at Sub-mmag Level



Photometric Pipeline Processes (2 of 2)



- **Long-Term Solutions**
 - **Combine Several Months of Data to Provide Corrections to CCD Column-by-Column Sensitivities Plus Magnitudes and Colors of All Stars**
- **Transformation to Standard System**
 - **FAME Instrumental System Will Be Transformed to SDSS System Using SDSS Secondary Standard Stars**



R&D Issues



- **Can Centroiding Be Done to the Required Single-Observation Accuracy? Depends on**
 - **How Rapidly the Optics Will Change With Time on Orbit**
 - **Degree and Functional Form of Spatial Variation of PSF and Lateral Color Separation Across Focal Plane**
 - **Lack of Significant S/C Rotational “Jitter” in the ~ 1 Hz Regime**
- **Can Changes in the Basic Angle Be Adequately Separated From Astrometric Parameters — Over the Spectrum of Basic Angle Variations Expected?**
- **Can We Do Absolute Calibration of the Photometry at the Required Accuracy With So Few (and Imperfect) Standard Candles?**
- **To What Extent Will the Overall Scheme of Iterative Solutions Propagate Systematic Errors in the Input Catalog or Instrument Models to the Final Astrometric Parameters?**